Quaternary International 380-381 (2015) 159–168

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

# Variability and extreme of Mackenzie River daily discharge during 1973–2011

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ARTICLE INFO

*Article history:*
Available online 25 October 2014

*Keywords:*
Long-term daily flow
Seasonal cycle
Arctic rivers
Mackenzie watershed

ABSTRACT

This study systematically analyzes long-term (1973–2011) daily flow data collected near the Mackenzie basin outlet. It clearly defines the variability, extreme events, and changes in daily flow records over the past 4 decades. The results of this study accurately determine the seasonal cycle of river discharge, including the range of highest and lowest daily flows. The interannual variation of daily flow is generally small in the cold season, highest in the spring melt period, and large over the summer months mainly due to rainfall storm activities and associated floods. This study also shows that Mackenzie River flow regime has changed over the past 4 decades due to climate variation, with the advance of snowmelt peak timing by several days, decrease in maximum spring flows by about 3000 $m^3/s$, and weak rise of cold season base flows. These results are the consequence of hydrological response to regional climate warming, and they provide new knowledge to improve our understanding of large-scale environmental changes over the broader northern regions.



## 1. Introduction

Climate warming is most significant over the past several decades in the northern regions. Climate models project a 1–4 C° global surface air temperature increase in the 21st century, with even greater increase in the Arctic regions (Kattsov et al., 2005; IPCC, 2013). This warming trend will impact the structure, function, and stability of both terrestrial and aquatic ecosystems and alter the land–ocean interaction in the Arctic. Arctic rivers are the dynamic component of the global climate system. Discharge from the Arctic rivers contributes as much as 10% to the upper 100 m of water column of the entire Arctic Ocean. The amount and variation of this freshwater in flow critically affect the ocean salinity, surface temperature, and sea ice formation, and may also exert significant control over global ocean thermohaline circulation (Aagaard and Carmack, 1989).

Arctic hydrologic systems exhibit large temporal variability due to changes in large-scale atmospheric circulation and poleward moisture transport (Saito et al., 2013; Zhang et al., 2013). This variation (particularly extreme events) significantly influences the cross-shelf movement of water, nutrients and sediments. Examination of streamflow regime and change in the major northern river basins and their relations to surface climate and atmosphere are critical to better understand and quantify the atmosphere–land–ocean interactions in the Arctic and consequent global impacts. Many studies report remarkable changes in water cycle components of the northern hydrology systems, such as increases of Eurasian Arctic river discharge (Peterson et al., 2002; McClelland et al., 2006), discharge increases in winter and decreases in summer for the Yenisei, Lena, Ob' watersheds in Siberia (Ye et al., 2003; Yang et al., 2004a,b), earlier melt of snow cover (Yang et al., 2007; Brown and Mote, 2009; Shi et al., 2013) and river ice breakup (Bonsal et al., 2006; Prowse et al., 2010), shift of peak flows in the spring season (Yang et al., 2007; Ge et al., 2012), and record high floods in 2007 for the large Siberian rivers (Shiklomanov and Lammers, 2011) along with an extreme loss of Arctic summer sea ice (Comiso et al., 2008). Ge et al. (2012) found that Yukon River annual flow increase by 8% over the past 40 years; summer flows have a higher fluctuation, and peak snowmelt flow slightly increases with its timing shifted to an earlier date. These changes in streamflow hydrology features are caused by climate variations and human impacts, particularly winter flow increase as the result of reservoir storage and regulation in Siberian regions (Ye et al., 2003, Yang et al., 2004a,b).

Streamflow records observed at the watershed outlet reflect basin integration of both natural variations and human-induced changes, such as changes of land cover/land use and regulations of large dams within the watersheds. Discharge data collected at

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http://dx.doi.org/10.1016/j.quaint.2014.09.023
1040-6182/

the river mouth are particularly important as they represent freshwater input to the ocean and are often used for basin-scale water balance calculations, climate change analysis, and validations of land surface schemes and GCMs over large spatial scales. It is therefore important to understand the fundamental characteristics, including temporal variations and changes in basin streamflows at various time scales (such as daily, monthly, yearly to decadal time steps). Many studies use monthly and yearly flow data to examine and document arctic hydrology changes (Lammers et al., 2001; Peterson et al., 2002; Ye et al., 2003; Yang et al., 2004a,b; McClelland et al., 2006; Adam et al., 2007; Shiklomanov et al., 2007; Rawlins et al., 2010) and biogeochemical processes (Liu et al., 2005; Holmes et al., 2012; Tank et al., 2012). It has been recognized that monthly flow data and analyses are not always suitable for hydrological process investigations over the cold regions, especially during the spring snowmelt period that may last from a few weeks up to several weeks, and summer rainfall floods (most often lasting up to a few days to a week). Yang et al. (2002) used daily, monthly, and annual flow data to study Lena river hydrology changes; their analysis of the long-term daily discharge records at the Lena basin outlet confirms an advance of snowmelt peak flood from June toward late May. Yang et al. (2003) also generated weekly flow data from the daily records for the large Siberian Rivers and compared them with weekly snow cover extent and SWE data, and established regression relationships between snowmelt and spring season flows. These relationships are useful for the prediction of spring flows over the large northern regions.

River flows significantly vary at the inter-annual time scale in the arctic regions. Daily flow data are necessary to accurately

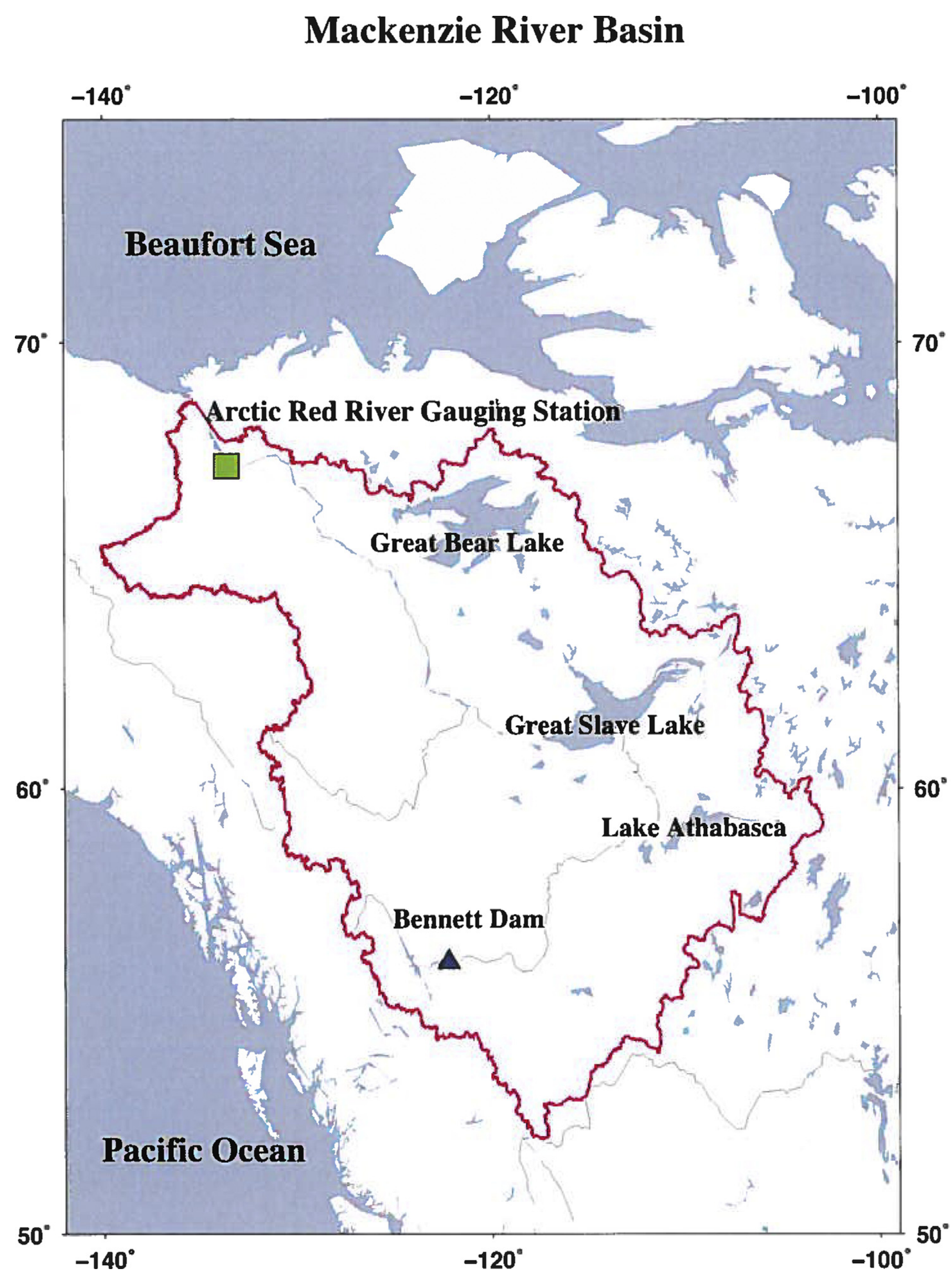


**Fig. 1.** The Mackenzie River system, including major sub-basins and locations of large lakes, reservoir, and the Arctic Red River gauging station near the basin outlet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

document discharge seasonal cycle and its change. Daily discharge data are also useful for the determinations of river heat and chemistry fluxes that depend on the streamflow fluctuation, water temperature, and chemical concentration (Liu et al., 2005; Lammers et al., 2007; Holmes et al., 2012; Tank et al. 2012). This study assesses the Mackenzie River daily flow variability and its change over time. The focus of this analysis is on the basin scale (as a whole at the outlet control station) to improve our understanding of the integrated, large-scale hydrologic processes in the northern regions. It systematically analyzes long-term (1973–2011) daily discharge records collected near the Mackenzie River outlet, so as to quantify the annual and seasonal freshwater fluxes to the Arctic Ocean and their interannual variation and long-term changes. Specifically, this work will characterize river discharge regime at the daily time scale, and document flow variability, including extremes and changes over the past 40 years. This study will also discuss the key processes of interaction and feedback between climate and hydrology, particularly snow cover and river flow in the northern regions, thus providing new knowledge of northern river freshwater variability and change. The results of this work are useful for the development and validation of ocean/land surface models, large-scale water budget analyses, and hydro-climate change investigations in the arctic regions.

## 2. Basin, data, and methods

The Mackenzie is the largest northward flowing river in North America (Fig. 1). It drains an area of 1.8 million km$^2$, about 1/5 of the total land area of Canada. Its headwaters, covering parts of British Columbia, Alberta, Saskatchewan and the Northwest Territories, collect a vast system of rivers which flow into Great Slave Lake, from which the Mackenzie River proper flows in a northwesterly direction for about 1600 km before discharging through the Mackenzie Delta into the Beaufort Sea. The freshwater contribution is about 325 km$^3$/year, or approximately 7% of the annual in flow to the Arctic Ocean as a whole. This freshwater input and its distribution may affect sea ice melt process (Nghiem et al., 2014). The physical features of Mackenzie River basin vary widely from the Rocky Mountain system to the flat, mainly treeless wastes of the barren lands. Permafrost and wetland cover approximately 75% and 49% of the basin. Pingos and pattern-ground features associated with continuous permafrost are found in the north, while agriculture and forestry are important economic activities in the southern parts of the basin. The basin has several climatic regions, including cold temperate, mountain, subarctic, and arctic zones. Mean annual temperatures vary from around −10 C to 4 C, and annual precipitation ranges from more than 1000 mm in the southwest to about 200 mm along the arctic coast, average about 410 mm per year (Woo and Thorne, 2003, 2014).

There are many lakes in the basin. The three large ones are Lake Athabasca, Great Slave, and Great Bear lakes, with surface areas of $79.12 \times 10^3$, $28.6 \times 10^3$ and $31.3 \times 10^3$ km$^2$ respectively. These lakes are integral parts of the drainage network and they provide natural regulation to the system. One large reservoir (the Williston Lake reservoir, surface area $\approx 1.8 \times 10^3$ km$^2$) has been built in the upper Peace River, and outflow at Bennett Dam is regulated for power production. This regulation may substantially influence the water level fluctuations in Great Slave Lake; but did not significantly affect the flow conditions at the lower Mackenzie (Peters and Prowse, 2001; Woo and Thorne, 2003). Recent work by Woo and Thorne (2014) reports that the release of water from Peace River at the Bennett Dam provides 40–60% of the winter flow of the Mackenzie River. This result seems to suggest significant dam effects over the winter season.

The Water Survey of Canada (WSC) has gauged the Mackenzie River at several locations along its main trunk since early 1970's. The flow at the gauge of Arctic Red River combines the regimes of its sub-basins. Discharge data collected at this location (Fig. 1), before the river branches into many distributaries, are considered as the total flow for the Mackenzie River system. The entire daily flow records for this station, available to all users including the general public at the hydrometric database (HYDAT) for the period of 1973–2011, have been obtained and used for this study. This study also used precipitation data from the extended University of Washington gridded dataset (Shi et al., 2013), which originates from the University of Delaware (UDel) land precipitation product (Matsuura and Willmott, 2009). The UDel product is adjusted for gauge undercatch since solid precipitation is typically underestimated in the cold season by 10%–50% (Adam and Lettenmaier, 2003; Adam et al., 2006; Yang et al., 2005). The gridded precipitation data for the Mackenzie River Basin are averaged across the watershed during the water years (1972/73–2006/07).

The Mackenzie River has been the focus of many climate and hydrology research programs and projects, including the Mackenzie GEWEX Study (MAGS) (Woo et al., 2008a,b). Rawlins et al. (2009) examined the freshwater anomalies through the air–land–ocean system in the extremes discharge years. Lesack et al. (2014) reported the earlier ice breakup during 1974–2011 over the Mackenzie delta due to local spring warming and snowfall decrease. Prowse et al. (2010) documented changes in spring air temperature gradients along the main trunk of the river and discussed the implications for the severity of river ice floods. Nghiem et al. (2014) investigated the effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea and found warm waters intrusion from the Mackenzie River impacts sea ice melt. Yang et al. (2014) determined the basin water temperature regime and calculate the heat input to the Arctic Ocean.

This paper, based on the most updated long-term daily flow data for the Mackenzie River, complements other large-scale hydrological studies for the northern regions. This study uses various statistical approaches for data analyses to calculate the mean, and standard deviation of the daily discharge records. It also carries out trend analysis and statistical significance test to identify long-term changes. It applies a linear regression to daily discharge records to determine its changes as a function of time (year). The total trend is defined by the difference of flows shown on the regression line between the last year and the first year. The standard *t*-test is used to determine the statistical significance of the trends. This method has been used to study the flow changes for other northern rivers (Yang et al., 2002, 2003). This work also identifies the extreme flow cases (years) and determines the difference between the extremes, in order to define the range of daily flow variability over time. Through comparisons of our results to other relevant studies over the northern basins, such as the Lena and Yukon Rivers, this paper presents new information and knowledge that will improve our understanding of variability and changes in the arctic hydrology system.

## 3. Results

Long-term daily discharge records at the Arctic Red River station are available for this study. Fig. 2 shows all daily discharge data for the period 1973–2011. It is clear that the daily flows in the cold season (November to April, or Julian day (JD) 301–120) are very low and do not vary much over the season. This is because the low flows in the cold season are dominated by groundwater (baseflow) that does not change significantly in winter. For the warm season (May to October, JD 120–300), daily flows peak in the spring to early summer due to snowmelt and breakup of river ice (JD 135–185),

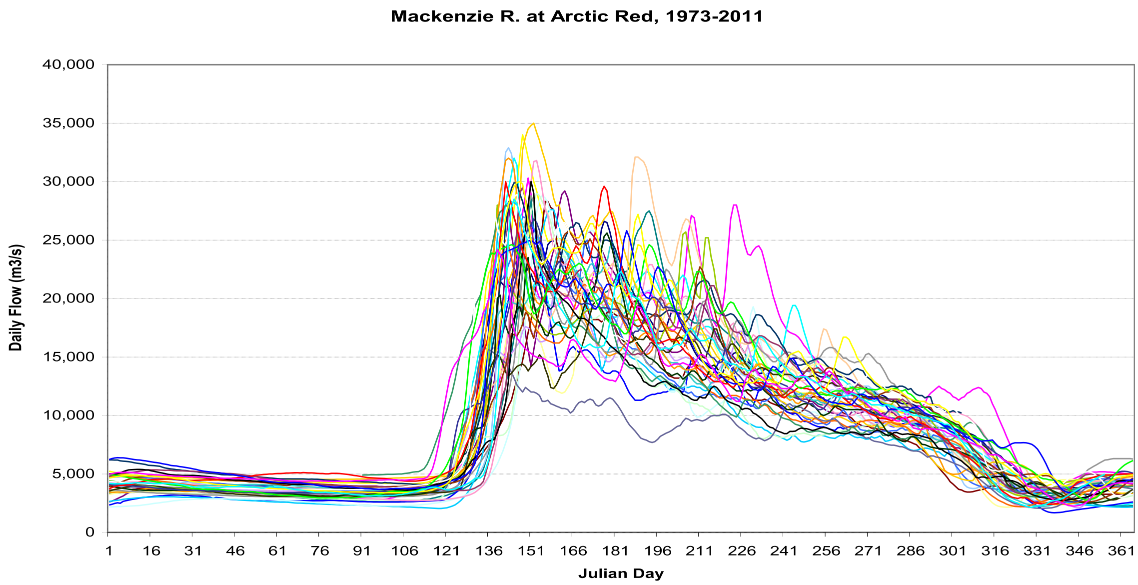


**Fig. 2.** Mackenzie River daily hydrographs during the period 1973–2011.

and summer flows are also high due to rainfall contributions. The daily flows over the warm season are quite different among the years, mainly due to the large interannual variations in spring snowmelt process and summer rainfall fluctuation.

Due to climate change in the northern regions, it is very important to study the extreme hydrological events and processes. We select two years with extreme (highest and lowest) daily peak flow conditions. Fig. 3 presents the daily hydrographs for the two selected years. The lowest peak flow year was 1995, with the daily maximum being about 16,000 $m^3/s$ on JD 127. This extreme year has been studied in the MAGS project. The low discharge reflects both negative anomalies in P–E and a pattern in which recycled summer precipitation fell over the southern part of the basin, characterized by low runoff ratios and dry surface conditions immediately prior to the water year (Liu et al., 2002; Louie et al., 2002). Rawlins et al. (2009) also examined the monthly P–E for the selected years, including 1995, and concluded that the record low flow in 1995 was largely the result of negative P–E anomalies from June to September, particularly in June and July. Negative P–E anomalies indicate relatively dry surface conditions over the basin and also lower flows, and low runoff ratio for the years. Negative anomalies in summer precipitation recycle also suggest less rainfall and dry conditions associated with the low flows.

On the other hand, the highest daily flow year was 1992, with the daily peak of 35,000 $m^3/s$ on JD 152. To examine the possible reasons for the extreme flows, we used two methods to calculate the winter total snowfall from 1972/73 to 2006/07 (water year). One is the sum of total monthly precipitation from October to May; the other is total daily precipitation for those days with air temperatures below 0 °C. The results are consistent; they both

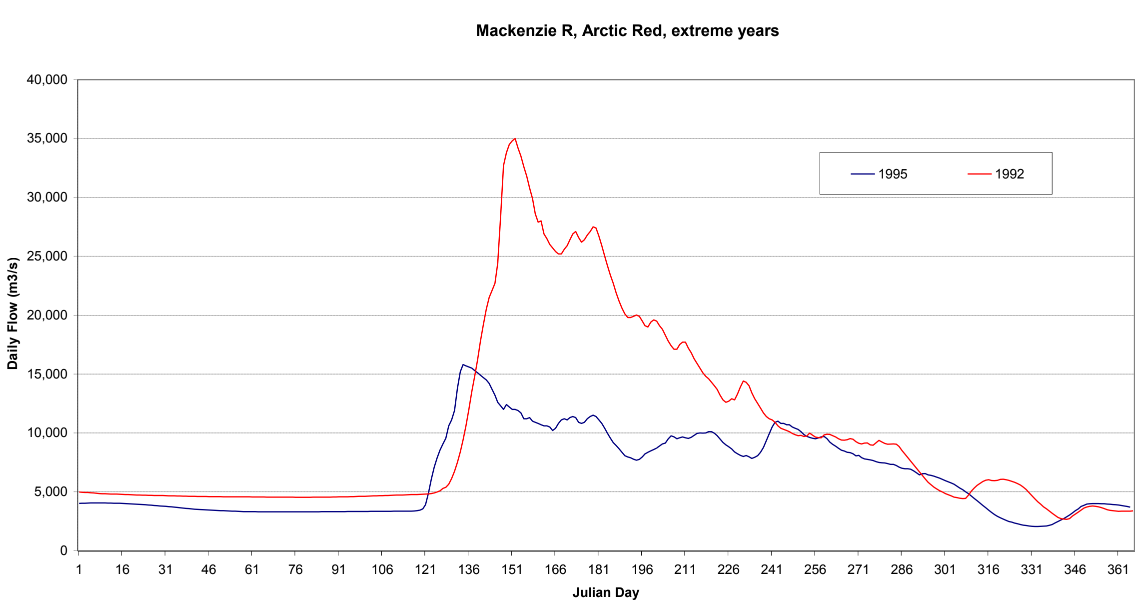


**Fig. 3.** Comparison of extremely high and low daily discharge years, 1992 vs. 1995.

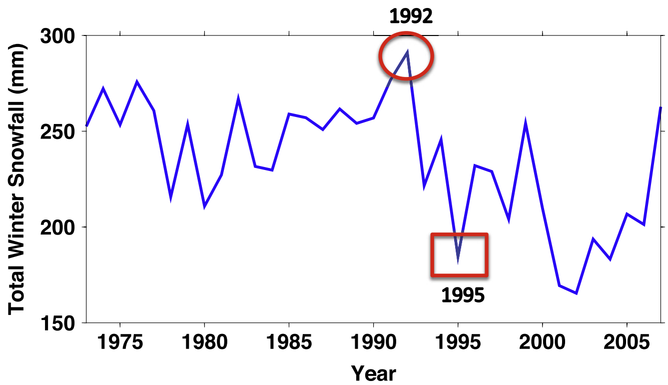


**Fig. 4.** Basin total winter snowfall during water years 1972/73 to 2006/07, with the highlight of the higher and lower snowfall years.

show highest snowfall winter for 1991/92, while 1994/95 was one of lowest snowfall years for the period 1973–2007 (Fig. 4). In addition, we also found that monthly SSMI data also suggest higher basin SWE (about 10 mm anomaly) at the end of 1991/92 winter season. Based on these data, the highest peak flow in 1992 was very likely due to the higher snowpack and fast melt over the spring season.

It is important to note the very large difference in both magnitude and timing of the peak flows, i.e. 16,000 $m^3$/s on JD 127 vs. 35,000 $m^3$/s on JD 152, between the lowest and highest years (Fig. 3). In terms of volume, the Mackenzie River at the Arctic Red River station transports 292 $km^3$ freshwater per year during 1973–2011; the basin outflows were, respectively, 316 $km^3$ in 1992 and 205 $Km^3$ in 1995. The difference in annual flow volumes between 1992 and 1995 is statistically significant at 90% level. This result is useful for many other applications, including the determination of the boundary condition for ocean water budget and model analyses (Dean et al., 1994).

To better understand daily flow characteristics, we calculate the mean, maximum and minimum discharge, and the standard deviation. Fig. 5 presents the result of daily flow statistics. The mean flows show a smooth hydrograph, with the highest flows (about 23,000 $m^3$/s) in the spring snowmelt season, higher flows in summer, and a gradual flow recession in fall to the winter season (baseflow 4000 $m^3$/s). The minimum and maximum flows are, respectively, the lowest and highest daily values in the records for each day. In other words, they are the extremes in the daily flow records and define the range of daily flow fluctuation. The pattern of the minimum flows is similar to that for the mean daily flows, with a peak value (about 12,000 $m^3$/s) in the spring and recession in the summer and fall. The maximum flows also peak in the spring (about 35,000 $m^3$/s), and fluctuate over the summer season due to heavy rainfall events over the basin. It is important to notice the huge difference among the mean and extreme flows particularly during the snowmelt season. For instance, taking the minimum flow as the reference, the mean peak spring flow is about 100% higher, and the maximum peak flow is roughly 300% higher.

Summer floods are critical for basin hydrology and regional water resources management. According to past studies (Liu et al., 2002; Louie et al., 2002), Mackenzie basin annul total precipitation is about 350–500 mm, and summer rainfall ranges from 40 to 55 mm during July to August. Due to data limitation, daily basin rainfall data are not available for most years. Cao et al. (2002) examined the extreme low spring flow in water year 1994/95, and reported daily rainfall intensity in the range of 0.5 mm/day–5 mm/day. They found summer flow rises in response to rainfall events of 20–25 mm over the basin. Another study in a small basin in northern Alaska indicated discharge response to rainfall of 15–25 mm over several days (Kane et al., 2000). The Mackenzie River is very large with different climatic and physical conditions among the sub-basins; basin runoff generation and flooding processes are complex. However, better rainfall data with finer time resolution will allow improved understanding of summer floods over the northern regions.

The standard deviation (STD) of the daily flows ranges from 570 $m^3$/s in winter to 6675 $m^3$/s in summer, with the highest value in the snowmelt period (Fig. 5), clearly indicting a large interannual variation in basin snowmelt and ice breakup processes. There are also weak fluctuations in the STD values over the summer

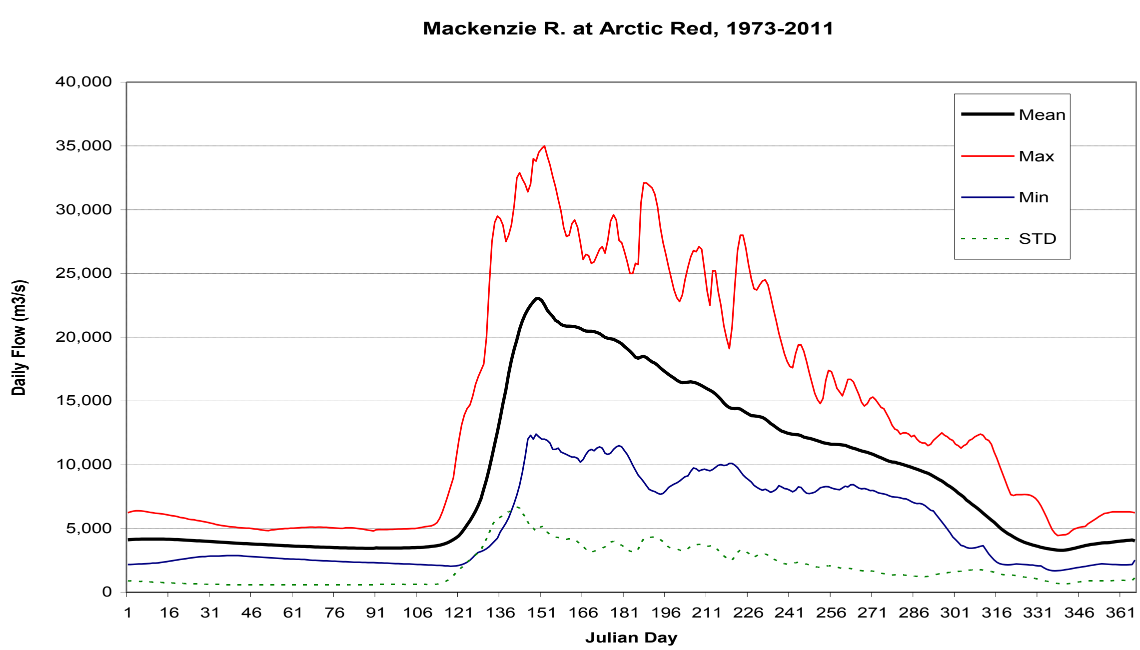


**Fig. 5.** Daily max, min and mean flows, and standard deviation during 1973–2011.

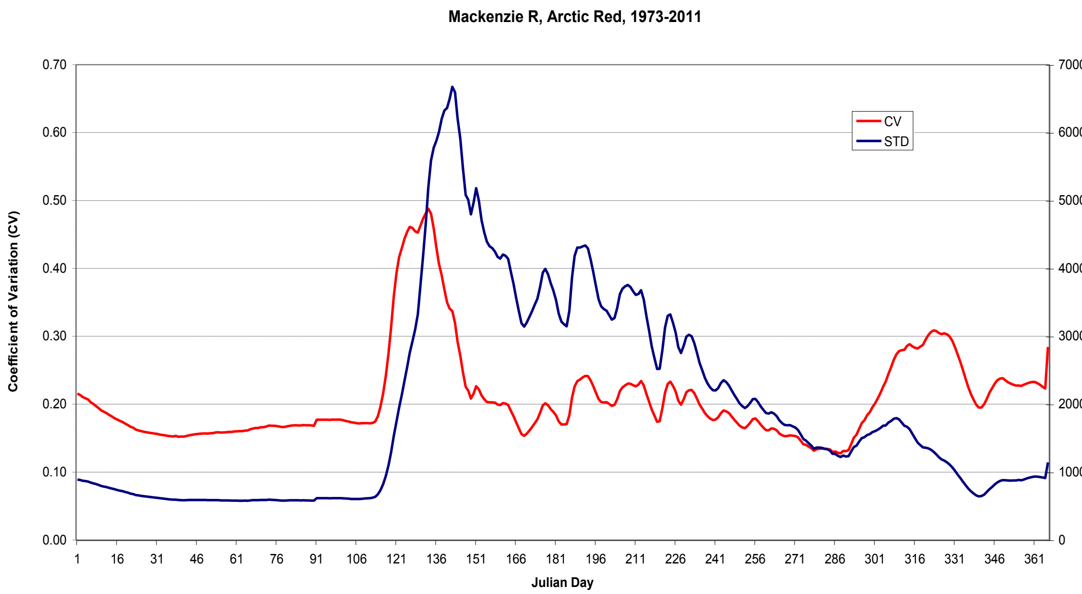


**Fig. 6.** Comparison of daily flow standard deviation (STD) and the coefficient of variation (CV).

season as the result of rainfall inputs and impacts. The coefficient of variation (CV) is another measure of discharge viability. Our analysis shows the daily CV varies from about 15% to 50% of the mean daily flows. It is interesting to point out the difference between the CV and STD patterns. Unlike the STD, the CV has two peaks; one in spring (around JD 110–145) and the other in fall (about JD 300–340). The first peak (about 50% on JD 133) appears by about 10 days before the STD spring peak (on JD 143); the second peak is about 30%, weakly corresponding to the STD pattern during November to December. The summer CV values are relatively lower (about 20%) mainly due to higher flows, although the STDs are higher in the summer season (Fig. 6).

To examine the changes in basin hydrologic features, Fig. 7 displays the time series of the mean, minimum and maximum daily flows, and the Julian day (JD) for the spring peak flows. There are large variations over time in the peak daily flows, with the lowest and highest being 15,800 $m^3/s$ and 35,000 $m^3/s$, respectively. The peak timing was mostly in May, but sometimes in June due to late melt of snow cover over the basin. Trend analyses reveal a statistically significant (85% confident) tendency of decreasing peak flow by about 3000 $m^3/s$ over the study period. Spring peak flows are closely related with the ice breakup. Analysis of breakup phenology of the Mackenzie River has found that breakup characteristics during 1970–2002 have become significantly earlier (de Rham et al., 2008). Breakup severity at the Mackenzie River mouth has declined in recent decades (Emmerton et al., 2007; Goulding et al., 2009), although sea level changes may also play a role at this river–ocean interface. Spring snowmelt is the most significant hydrological event in the northern basins, as it contributes large amount (up to more than 50% of total flow in some arctic basins) (Yang et al., 2003). We calculate the ratios of maximum daily flow to annual mean flow for the Mackenzie basin; they range from 2.3 to 3.8 over the past 4 decades. With decreasing daily peak flows, this ratio dropped by 0.5 (or 8%) during 1973–2011 (Fig. 8).

The timing for the peak daily flows varies greatly as well, from JD 135 to 188 in the spring to early summer; peak timing advanced by about 5 days over the period 1973–2011 (Fig. 7). Our results, i.e. decrease peak flow amount and the advance in timing over the Mackenzie, are consistent with other studies for the large northern regions and rivers (Ye et al., 2003; Yang et al., 2004a,b; Prowse et al., 2010; Ge et al., 2012). They are likely the responses of river system to regional climate warming particularly over the cold season – fall to spring. It is important to explore the relationship between and peak flow amount and its timing for the northern regions. Snowmelt process affects the magnitude of basin spring peak flows. Field observations in northern Alaska show that an early snow cover reduction may indicate a warmer spring or a thinner snowpack, and a late melt/decline may be due to a cold spring or a thicker snow cover (Kane et al., 2000). Comparisons of snowmelt timing with weekly mean peak flows reveal an association of high (low) flood peak with late (early) snowmelt in the Ob' basin (Yang et al., 2003). These studies indicate variations in peak flow responses to snow cover melt among the northern regions perhaps due to regional variations and differences in streamflow characteristics, and snow cover and climate conditions. There is a need to better understand snowmelt and runoff generation over the large northern watersheds with a significant warming.

The minimum daily flows (usually in the winter season) ranges from 1680 to 4090 $m^3/s$ over the study period. The inter-annul variation is much smaller than that for the maximum daily flows. There is a weak tendency of the minimum daily flow increase during 1973–2011 (Fig. 7). This change in flow amount is very small and statistically insignificant; it is thus almost undetectable in terms of its contribution to the total flow, i.e. stable ratios of minimum daily flow/mean daily flow over the study period (Fig. 8). Baseflow increase has been reported for the northern regions and NWT, Canada due to recent climate warming (Woo et al., 2008a,b; St. Jacques and Sauchyn, 2009). Yang et al. (2014) discovered Mackenzie basin monthly discharge increases during September to April. Basin storage changes affect low flow and baseflow conditions and their changes. The Mackenzie basin has large seasonal storages due to many large lakes in the basin. The increases in the monthly and daily low flows may reflect changes in the basin storages, including lakes, groundwater, and permafrost and ground ice.

The mean daily flows vary from 6500 to 12,300 $m^3/s$ over the study period; they show little trend, except a weak increasing tendency over the study period (Fig. 7). The daily mean flows

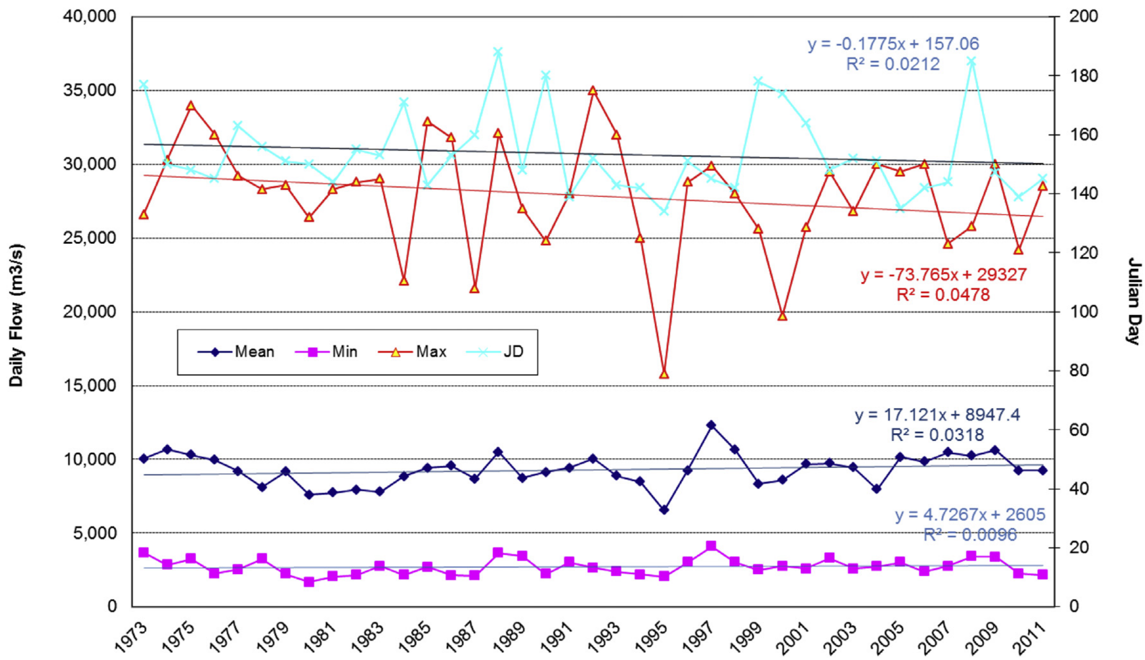


**Fig. 7.** Time series and trends of daily max, min, mean flows, and the peak flow date in Julian day, 1973–2011.

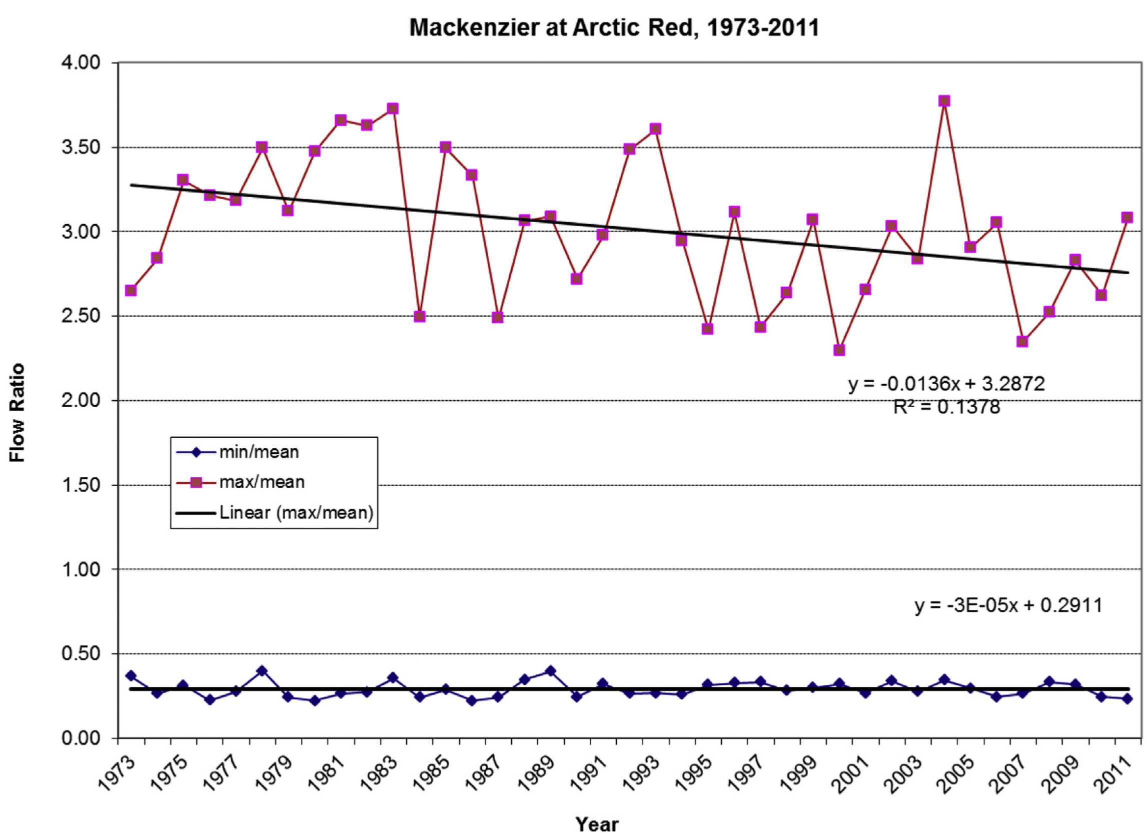


**Fig. 8.** Time series and trends of ratios of daily max/daily mean flows, and daily min/daily mean flows, 1973–2011.

represent basin annual total discharge. Other studies report minor changes in the Mackenzie basin streamflows. Woo and Thorne (2003) concluded that Mackenzie River flows during 1975–2003 did not have obvious trends at annual or monthly time scale, but significant changes in flow variability occurred for several sub-basins in different months. There is also evidence of an earlier breakup in the past few decades may be related with increasing spring temperatures during the snowmelt and river ice breakup (Lesack et al., 2014). Yang et al. (2014) found Mackenzie monthly flows during 1975–2011 increased from September to May,

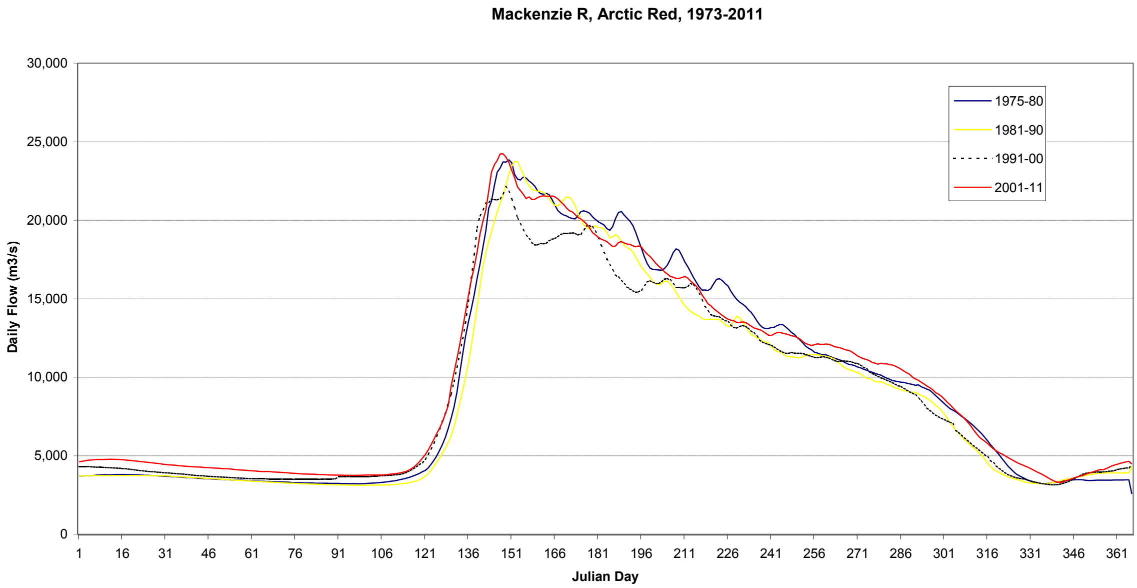


**Fig. 9.** Comparison of decadal mean daily flows for the Mackenzie River, 1973–2011.

decreased over the summer months, and overall the total flows did not change much.

Many studies investigate climate variability at the decadal time scales over the northern regions (Serreze and Francis, 2006). In order to understand hydrological response to climate variation and change, including hydrologic regime and its change, systematic analyses of the long-term daily discharge records at various time scales are useful. In this study, we calculate the decadal mean daily flows over the past 4 decades, and compare them in Fig. 9 for the Mackenzie River. The results show similar flow patterns over time and some visible differences in flow characteristics. For instance, winter base flows increased gradually over time, with the higher values in the past 2 decades, particularly during JD 1–115. This result is consistent with the weak increase in the minimum daily flow (Fig. 7). The timing of flow rise over the spring snowmelt season advanced by a few days over the past 4 decades. The timing of maximum flows also became earlier, although the peak flow amounts were similar for the most time periods, except lower values in the 1990s. On the other hand, summer flows were lower in the 1990's, but higher during 1975–80, with 3–4 higher flow events perhaps due to heavy rainfall inputs. These changes in the flow characteristics suggest a hydrologic regime shift toward earlier snowmelt and early summer peak flow season. This result is in agreement with other studies, as Yang et al. (2002) and Ge et al. (2012) found an advance of snowmelt peak flows of the Lena and Yukon rivers over the past several decades.

## 4. Summary and discussion

This study systematically analyzes long-term (1973–2011) daily flow data collected near the Mackenzie basin outlet. It clearly determines the seasonal patterns of discharge and its contributions to the Arctic Ocean, and quantifies the variability and change over the past 4 decades. It also examines and compares the extremely high and low flow years, thus providing constraints or boundary conditions for ocean water and heat budget calculations and modeling validations (Dean et al., 1994). The results of this study accurately describe the seasonal cycle of river discharge, including the range of possible high and low daily flows. The interannual variation of daily flow is generally small in the cold season, the highest in the spring melt period, and large over summer months mainly due to rainfall storm activities and associated floods. This study shows that Mackenzie River flow regime has changed over the past 4 decades due to climate variation, with the advance of snowmelt peak timing by a few days, decrease in maximum spring flows, and rise of cold season base flows. These new results support recent studies for the Mackenzie River, such as earlier river ice breakup of the Mackenzie Delta (Lesack et al., 2014), changes in basin and sub-basin streamflow characteristics (Woo and Thorne, 2003, 2014); they also complement and enhance other hydrology change investigations for the large arctic rivers in Siberia and Alaska (Yang et al., 2002; Ye et al., 2003; Ge et al., 2012).

This study is possible owing to the long-term flow data collections in the Mackenzie River basin. Consistent hydrometric and climatic observations and records are essential for global change research particularly over the vast northern regions with the sparse monitoring networks. Past studies mainly use monthly and yearly discharge data to describe hydrological regimes (including seasonality) and changes over the northern regions. It is known that daily flow data are necessary to better represent streamflow characteristics (Yang et al., 2002; Shiklomanov et al., 2007; Ge et al., 2013), since monthly flow data do not fully represent flow processes, particularly the fast processes, such as the snowmelt and summer heavy rainfall floods. Yang et al. (2014) recently examine long-term daily flow records near the Yukon River outlet during 1975–2008 and find low flows in the cold season with little variation, because baseflow is dominated by groundwater that does not change significantly over the winter. However, for the warm season (May to October), daily flow fluctuations are quite large among the years due to snowmelt, glacier melt, and rainfall variations.

Fig. 10, as an example, compares the mean daily and monthly flows for the Mackenzie River. It is very clear that daily data show more information of flow changes particularly over the snowmelt period (roughly JD 120–160), and they are thus much better than the monthly records to accurately characterize discharge seasonal cycle and its variation. It is important to mention that long-term daily flow records have been collected for many large northern rivers and regions; and they become available through online data distribution and exchange. There have been efforts to use daily flow records, in combination with climate data, for accurate

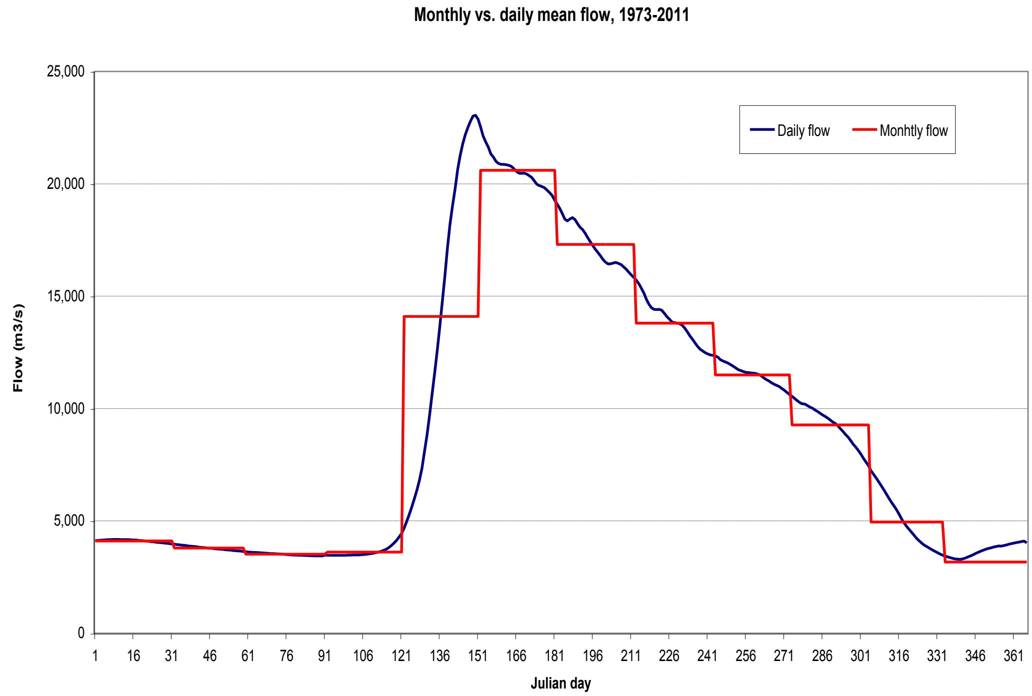


**Fig. 10.** Comparison of daily mean flow and monthly mean flow for the Mackenzie River, 1973–2011.

quantifications of basin and regional hydrologic changes. For instance, Smith et al. (2007) analyzed daily discharge data for 111 northern rivers from 1936 to 1999 and 1958 to 1989, and found overall increases in minimum daily flows. The minimum flow increases occurred in both summer and winter, and in non-permafrost and permafrost terrains. There were no robust spatial contrasts between the European Russia, Ob', Yenisey, and Lena/eastern Siberia sectors. These increases were generally more abundant relative to the increases in mean flow; they may affect the overall rise in mean flow. The minimum flows are sensitive to groundwater and unsaturated zone inputs to river discharge, this result may suggest a possible mobilization of such water sources in the late 20th century. On the other hand, floods cause more damage in Russia than any other natural disaster, and future climate model projections suggest increases, with climate warming, in the frequency and magnitude of extreme hydrological events in Russia. Shiklomanov et al. (2007) examined the daily discharge records at 139 Russian gauges in the Eurasian Arctic drainage basins regarding changes in maximum discharge. They reported relatively equal numbers of significant positive and negative trends across the Russian Arctic drainage. They also observed a significant shift to earlier spring discharge, which is consistent with documented changes in snowmelt and freeze–thaw dates. Spatial analysis of changes in maximum discharge and cold season precipitation revealed consistency across most of the domain. Trends in maximum discharge of the small – to medium-sized rivers were generally consistent with the aggregated signals for the downstream gauges of the six largest Russian rivers. Although they observed regional changes in maximum discharge across the Russian Arctic, they concluded that no evidence of widespread trends in extreme discharge can be assumed from their analysis.

Climate fluctuations and human activities affect basin hydrologic conditions and its changes. Many studies demonstrate that discharge trends may depend on climate factors, such as precipitation, snow cover, and temperature changes (Ye et al., 2003; Yang et al., 2004a,b; Ge et al., 2012). Human activities, such as reservoir regulation and water uses for agriculture and industry, also affect flow regimes and its changes in both the northern regions (Ye et al., 2003; Yang et al., 2004a,b; McClelland et al., 2006; Woo et al., 2008a,b) and over the large Asian rivers (Lu et al., 2013; Lu and Jiang, 2014). It is a challenge to determine and separate the effects of human activities and climate variations on regional flow changes (Yang et al., 2004a,b; Lu et al., 2013; Lu and Jiang, 2014). Basin hydrologic and climatic analyses are useful to quantify changes and linkages over various parts of sub-basins (Ye et al., 2003; Woo and Thorne, 2003, 2014; Yang et al., 2005). Relative to the large Asian rivers, human activities and their effects are less significant in the Mackenzie River. This study focuses on the downstream flow regime and change of the Mackenzie River where dam regulation is weak. The results of this work are particularly important for the analyses of basin water budget and freshwater input to the Arctic Ocean. They are also useful for comparative studies of large river hydrology and its changes between the northern and mid latitudes.

## Acknowledgment

We would like to thank the Water Survey of Canada for supplying discharge data to this study.

## References

Aagaard, K., Carmack, E.C., 1989. The role of sea ice and other fresh water in the Arctic circulation. Journal of Geophysical Research 94 (C10), 14,485–14,498.

Adam, J.C., Lettenmaier, D.P., 2003. Adjustment of global gridded precipitation for systematic bias. Journal of Geophysical Research 108, 4257. http://dx.doi.org/10.1029/2002JD002499.

Adam, J.C., Clark, E.A., Lettenmaier, D.P., Wood, E.F., 2006. Correction of global precipitation products for orographic effects. Journal of Climate 19, 15–38. http://dx.doi.org/10.1175/JCLI3604.1.

Adam, J.C., Haddeland, I., Su, F., Lettenmaier, D.P., 2007. Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei, and Ob' rivers. Journal of Geophysical Research 112 (D24), 114.

Bonsal, B.R., Prowse, T.D., Duguay, C.R., Lacroix, M.P., 2006. Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over Canada. Journal of Hydrology 330, 340–353.

Brown, R.D., Mote, P.W., 2009. The response of Northern Hemisphere snow cover to a changing climate. Journal of Climate 22, 2124–2145.

Cao, Z., Wang, M., Proctor, B.A., Strong, G.S., Stewart, R.E., Ritchie, H., Burford, J.E., 2002. On the physical processes associated with the water budget and discharge of the Mackenzie basin during the 1994/95 water year. Atmosphere-Ocean 40 (2), 125–143.

Comiso, J.C., Parkinson, C.L., Gersten, R., Stock, L., 2008. Accelerated decline in the Arctic sea ice cover. Geophysical Research Letters 35, L01703. http://dx.doi.org/10.1029/2007GL031972.

de Rham, L.P., Prowse, T.D., Bonsal, B.R., 2008. Temporal variations in river ice breakup over the Mackenzie River basin, Canada. Journal of Hydrology 349, 441–454.

Dean, K.G., Stringer, W.J., Ahlnäs, K., Searcy, C., Weingartner, T., 1994. The influence of river discharge on the thawing of sea ice, Mackenzie River Delta: Albedo and temperature analyses. Polar Research 13 (1), 83–94.

Emmerton, C.A., Lesack, L.F.W., Marsh, P., 2007. Lake abundance, potential water storage, and habitat destruction in the Mackenzie River Delta, western Canadian Arctic. Water Resources Research 43, W05419. http://dx.doi.org/10.1029/2006WR005139.

Ge, S., Yang, D., Kane, D.L., 2012. Yukon River Basin long-term (1977–2006) hydrologic and climatic analysis. Hydrological Processes. http://dx.doi.org/10.1002/hyp.9282.

Goulding, H., Bonsal, B., Prowse, T.D., 2009. Hydroclimatic controls on the occurrence of break-up and ice jam flooding in the Mackenzie Delta, NWT. Journal of Hydrology 379, 251–267.

Holmes, R.M., et al., 2012. Seasonal and annual fluxes of nutrient and organic matter from large rivers to the Arctic Ocean and surrounding seas. Estuaries and Coasts 35, 369–382.

IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.

Kane, D.L., Hinzman, L.D., McNamara, J.P., Zhang, Z., Benson, C.S., 2000. An overview of a nested watershed study in Arctic Alaska. Nordic Hydrology (4/5), 245–266.

Kattsov, V.M., et al., 2005. Future climate change: modeling and scenarios for the Arctic. In: Arctic Climate Impact Assessment. Cambridge University Press, Cambridge, U. K, pp. 100–150.

Lammers, R.B., Pundsack, J.W., Shiklomanov, A.I., 2007. Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass. Journal of Geophysical Research 112, G04S59. http://dx.doi.org/10.1029/2006JG000370.

Lammers, R., Shiklomanov, A., Vorosmarty, C., Fekete, B., Peterson, B., 2001. Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research 106 (D4), 3321–3334.

Lesack, L., Marsh, P., Hicks, F.E., Forbes, D.L., 2014. Local spring warming drives earlier river-ice breakup in a large arctic delta. Geophysical Research Letters 41. http://dx.doi.org/10.1002/2013gl058761.

Liu, B., Yang, D., Ye, B., Berezovskaya, S., 2005. Long-term open-water season stream temperature variations and changes over Lena river basin in Siberia. Global and Planetary Change 48 (1–3), 96–111.

Liu, J., Cho, H.-R., Stewart, R.E., 2002. Characteristics of the water vapour transport over the Mackenzie River basin during the 1994–95 water year. Atmosphere-Ocean 40, 101–111.

Louie, P.Y.T., Hogg, W.D., MacKay, M.D., Zhang, X., Hopkinson, R.F., 2002. The water balance climatology of the Mackenzie Basin with reference to the 1994/95 water year. Atmosphere-Ocean 40, 159–180.

Lu, X.X., Jiang, T., 2014. Larger Asian rivers: shorter and longer term hydro-climate changes in humid and arid environments. Quaternary International 336, 1–5.

Lu, X.X., Ran, L.S., Liu, S., Jiang, T., Zhang, S.R., Wang, J.J., 2013. Sediment loads response to climate change: a preliminary study of eight large Chinese rivers. International Journal of Sediment Research 28 (1), 1–14.

Matsuura, K., Willmott, C.J., 2009. Terrestrial Precipitation: 1900–2008 Gridded Monthly Time Series (Version 2.01). Center for Climatic Research, Department of Geography, University of Delaware. Newark, DE, digital media. [Available online at: http://climate.geog.udel.edu/~climate/.

McClelland, J.W., Déry, S.J., Peterson, B.J., Holmes, R.M., Wood, E.F., 2006. A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century. Geophysical Research Letters 33, L06715. http://dx.doi.org/10.1029/2006GL025753.

Nghiem, S.V., Hall, D.K., Rigor, I.G., Li, P., Neumann, G., 2014. Effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea. Geophysical Research Letters 41. http://dx.doi.org/10.1002/2013GL058956.

Peters, D.L., Prowse, T.D., 2001. Regulation effects on the lower Peace River, Canada. Hydrological Processes 15, 3181–3194.

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., Rahmstorf, S., 2002. Increasing river discharge to the Arctic Ocean. Science 298, 2171–2173.

Prowse, T., Shrestha, R., Bonsal, B., Dibike, Y., 2010. Changing spring air temperature gradients along large northern rivers: implications for severity of river-ice floods. Geophysical Research Letters 37, L19706. http://dx.doi.org/10.1029/2010GL044878.

Rawlins, M., Steele, M., Serreze, M.C., Vörösmarty, C.J., Ermold, W., Lammers, R.B., McDonald, K.C., Pavelsky, T.M., Shiklomanov, A., Zhang, J., 2009. Tracing freshwater anomalies through the air-land-ocean system: a case study from the Mackenzie River basin and the Beaufort Gyre. Atmosphere-Ocean 47 (1), 79–97.

Rawlins, M.A., et al., 2010. Analysis of the arctic system for freshwater cycle intensification: observations and expectations. Journal of Climate 23, 5715–5737.

Saito, K., Zhang, T., Yang, D., Marchenko, S., Barry, R.G., Romanovsky, V., Hinzman, L.D., 2013. Influence of the physical terrestrial Arctic in the eco-climate system. Ecological Applications 23 (8), 1778–1797.

Serreze, M.C., Francis, J.A., 2006. The Arctic amplification debate. Climate Change 76, 241–264.

Shi, X., Déry, S.J., Groisman, P.Y., Lettenmaier, D.P., 2013. Relationships between recent Pan-Arctic snow cover and hydroclimate trends. Journal of Climate 26, 2048–2064.

Shiklomanov, A.I., Lammers, R.B., Rawlins, M.A., Smith, L.C., Pavelsky, T.M., 2007. Temporal and spatial variations in maximum river discharge from a new Russian data set. Journal of Geophysical Research 112, G04S53. http://dx.doi.org/10.1029/2006JG000352.

Shiklomanov, A.I., Lammers, R.B., 2011. River Discharge, in Arctic Report Card 2011, pp. 156–161. Available at: http://www.arctic.noaa.gov/reportcard. accessed Jan. 2014.

Smith, L.C., Pavelsky, T.M., MacDonald, G.M., Shiklomanov, A.I., Lammers, R.B., 2007. Rising minimum daily flows in northern Eurasian rivers: a growing influence of groundwater in the high-latitude hydrologic cycle. Journal of Geophysical Research 112, G04S47. http://dx.doi.org/10.1029/2006JG000327.

St. Jacques, J., Sauchyn, D.J., 2009. Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. Geophysical Research Letters 36. http://dx.doi.org/10.1029/2008GL035822.

Tank, S.E., Raymond, P.A., Striegl, R.G., McClelland, J.W., Holmes, R.M., Fiske, G.J., Peterson, B.J., 2012. A land-to-ocean perspective on the magnitude, source and implication of DIC flux from major Arctic rivers to the Arctic Ocean. Global Biogeochemical Cycles 26, GB4018. http://dx.doi.org/10.1029/2011GB004192.

Woo, M.K., Thorne, R., 2003. Streamflow in the Mackenzie Basin, Canada. Arctic 56 (4), 328–340.

Woo, M.K., Rouse, W.R., Stewart, R.E., Stone, M.R., 2008a. The Mackenzie GEWEX Study: a contribution to cold region atmospheric and hydrologic sciences. In: Woo, M.K. (Ed.), Cold Region Atmospheric and Hydrologic Studies, the Mackenzie GEWEX Experience, Atmospheric Dynamics, vol. 1. Springer, Heidelberg, pp. 1–22.

Woo, M.K., Thorne, R., Szeto, K., Yang, D., 2008b. Streamflow hydrology in the boreal region under the influences of climate and human interference. Philosophical Transactions, Royal Society B 363.

Woo, M.K., Thorne, R., 2014. Winter flows in the Mackenzie drainage system. Arctic 67, 238–256.

Yang, D., Kane, D.L., Hinzman, L., Zhang, X., Zhang, T., Ye, H., 2002. Siberian Lena River hydrologic regime and recent change. Journal of Geophysical Research 107 (D23), 4694. http://dx.doi.org/10.1029/2002JD002542.

Yang, D., Robinson, D., Zhao, Y., Estilow, T., Ye, B., 2003. Streamflow response to seasonal snow cover extent changes in large Siberian watersheds. Journal of Geophysical Research 108 (D18), 4578. http://dx.doi.org/10.1029/2002JD003149.

Yang, D., Ye, B., Kane, D., 2004a. Streamflow changes over Siberian Yenisei river basin. Journal of Hydrology 296 (1–4), 59–80.

Yang, D., Ye, B., Shiklomanov, A., 2004b. Streamflow characteristics and changes over the Ob river watershed in Siberia. Journal of Hydrometeorology 5 (4), 69–84.

Yang, D., Kane, D., Zhang, Z., Legates, D., Goodison, B., 2005. Bias-corrections of long-term (1973–2004) daily precipitation data over the northern regions. Geophysical Research Letters 32, L19501. http://dx.doi.org/10.1029/2005GL024057.

Yang, D., Marsh, P., Ge, S., 2014. Heat flux calculation and analyses for Mackenzie and Yukon Rivers. Polar Science 8 (3), 232–241.

Yang, D., Zhao, Y., Armstrong, R., Robinson, D., Brodzik, M.-J., 2007. Streamflow response to seasonal snow cover mass changes over large Siberian watersheds. Journal of Geophysical Research 112, F02S22. http://dx.doi.org/10.1029/2006JF000518.

Ye, B., Yang, D., Kane, D., 2003. Changes in Lena River streamflow hydrology: human impacts vs. natural variations. Water Resources Research 39 (7), 1200–1215.

Zhang, X., He, J., Zhang, J., Polaykov, I., Gerdes, R., Inoue, J., Wu, P., 2013. Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. Nature Climate Change 3, 47–51.